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Laboratory Observations of Condensation in Wall Specimens

by

RICHARD S. DILL
and
HERMAN V. COTTONY

NATIONAL
BUREAU OF STANDARDS

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REPORT BMS 106

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ISSUED AUGUST 2, 1946

The National Bureau of Standards is a fact-finding organization; it does not "approve" any particular material or method of construction. The technical findings in this series of reports are to be construed accordingly

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Foreword

The importance of the relation between the permeability of vapor barriers and the heat-transfer characteristics of building walls has been emphasized by the increased use of insulating materials in dwelling houses and other buildings. This increase is traceable to the growing realization on the part of the public of the benefits to be attained by using these materials to improve comfort conditions in summer and to conserve heat in winter.

The installation of insulating materials in a building, however, is accompanied by a hazard in the form of possible damage to the structure by moisture resulting from condensation of water vapor within a wall, ceiling, or other building element. Condensation may destroy the efficiency of insulation and shorten its life; it may also cause rot in timbers.

In the investigation covered by this report the effects of condensation on several specimen walls were observed in the laboratory with the objective of finding ways of preventing moisture damage.

Eight different arrangements of insulation and vapor seal were tested, and the observations and conclusions are reported in this paper.

E. U. CONDON, *Director.*

Laboratory Observation of Condensation in Wall Specimens

by RICHARD S. DILL *and* HERMAN V. COTTONY

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ABSTRACT

Water-vapor migration and condensation in walls were investigated by means of a laboratory apparatus whereby a specimen wall was exposed to cold air on one side and to warm, humidified air on the other side. The wall was insulated and protected against water-vapor condensation in various ways for purposes of observation. The test conditions were a little more severe than those ordinarily expected anywhere in the continental United States.

The observed relation between vapor pressure and condensation and the observed effects of vapor barriers are described and discussed.

In this investigation, it was found that condensation occurred within a heavily insulated wall, but that conditions conducive to condensation within the wall structure could be avoided by the use of an effective vapor barrier or by ventilating the interior of the wall with cold air.

I. INTRODUCTION

The theoretical aspects of condensation in building walls have been treated previously in Building Materials and Structures Report BMS63, Moisture Condensation in Building Walls, and a survey of the humidities ordinarily maintained in houses in winter is covered in Building Materials and Structures Report BMS56, A Survey of Humidities in Residences. In addition, BMS63 contains a compilation of available data on the vapor permeability of various materials that are or may be commonly used in building construction. Upon examination, the data may show inconsistencies that would make conclusions based on them misleading. During the work covered by this paper the conditions within a wall structure, with special reference to dampness (water or ice deposits) and vapor pressure were observed by means of a laboratory apparatus constructed for the purpose. The wall was insulated in various ways and provided with several different means of preventing condensation of water vapor.

II. APPARATUS

Details of the apparatus constructed for this work are illustrated in figure 1. The apparatus consists essentially of a cold box cooled by a refrigerating coil, and a hot box heated electrically and enclosing a trough, or vat, containing a salt solution by means of which the humidity in the hot box is controlled. A wall specimen, installed for test in the position shown, is exposed to warm, humidified air on one side and to relatively cold air on the other. A sheet-copper diaphragm in the cold box located between the specimen wall and the cooling coil, serves to arrest and collect, for observation and weighing, the water that has passed through the wall in vapor form. The boxes are insulated with cork to minimize heat exchanges except through the specimen. The hot box is lined with sheet copper inside the cork to prevent vapor exchanges through its walls.

Temperatures in both boxes were automatically controlled. In the cold box, the supply of refrigerant (carbon dioxide) to the cooling coil was manually set slightly higher than necessary to maintain the desired condition. Electric heating coils with thermostatic switches

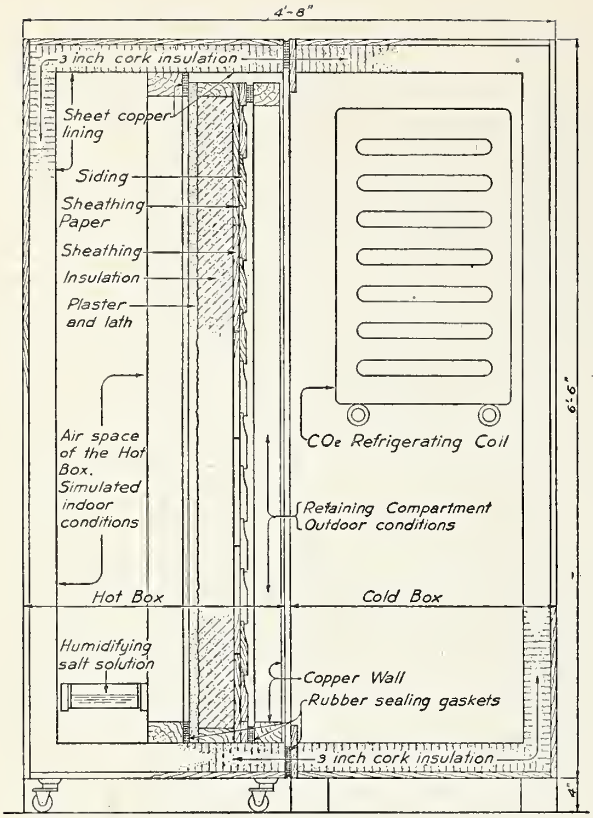

FIGURE 1.—*Longitudinal section of test apparatus.*

were used to offset the slightly excessive cooling effect and to afford sufficiently precise control. The heaters in the hot box were controlled by mercury-in-glass thermoregulators operating through relays.

Small electric fans were used in both boxes to set the air gently in motion and thus promote uniformity of temperature and humidity throughout the interior of each box.

A saturated solution of calcium chloride hexahydrate was used in the humidifying pan to maintain the selected humidity in the box.

The humidity in the hot box was measured by means of a dew-point hygrometer, a modification of a device described in Scientific Paper S500[1].[1] A metal mirror in the device was cooled by a stream of cold air until dew formed on the surface; the temperature of the mirror when this occurred was observed by means of a thermocouple. This temperature, being the dew point of the air to which the mirror is exposed, is an indication of the humidity in the box.

The permeabilities of materials used as vapor barriers were determined by the official method of the Technical Association of the Pulp and Paper Industry. This method involves a test at 23° C with one face of the material exposed to dry air and the other to air at 50-percent relative humidity. The results are usually expressed in grams (of water vapor transferred) per square meter during 24 hours.

III. TEST SPECIMEN

For the purpose of this work a specimen or panel, simulating ordinary frame-wall construction, was tested with eight different arrangements of insulation and vapor seal as indicated in table 1.

TABLE 1.—*Components of test specimens*

Tests	Insulation		Ventilation	Vapor barrier
	Material	Thickness		
A	Shredded bark.	3⅝ in.	None	None.
B	do	3⅝ in.	do	60-lb asphalt-saturated kraft.
C	Aluminum foil.	1 sheet	do	None except aluminum foil.
D	Rock wool	3⅝ in.	Holes top and bottom.	None.
E	Wood-fiber blanket.	Two 1-in.	None	None except covering on blankets.
F	Rock wool	3⅝ in.	do	None.
G	do	3⅝ in.	do	Two-ply untreated kraft.
H	do	3⅝ in.	do	Two-ply asphalt-saturated kraft.

The test panel, the construction of which is shown in figure 2, was made of conventional materials. The frame was 2- by 4-in. Douglas fir, the inside face was plaster on metal lath, and the outside face was shiplap siding on sheathing, with sheathing paper (60-lb saturated kraft) between. The sheathing was No. 2 white pine and the siding was Douglas fir. None of the parts was painted. The panel was fastened together with wood screws, instead of nails, to facilitate assembling and dismantling.

Three wooden plugs, each 2 in. in diameter, were fitted into holes bored for the purpose in the sheathing, as shown in figure 2. These plugs served to indicate changes in moisture content of the sheathing, as they formed a part of the

[1] Figures in brackets indicate the literature references at end of this paper.

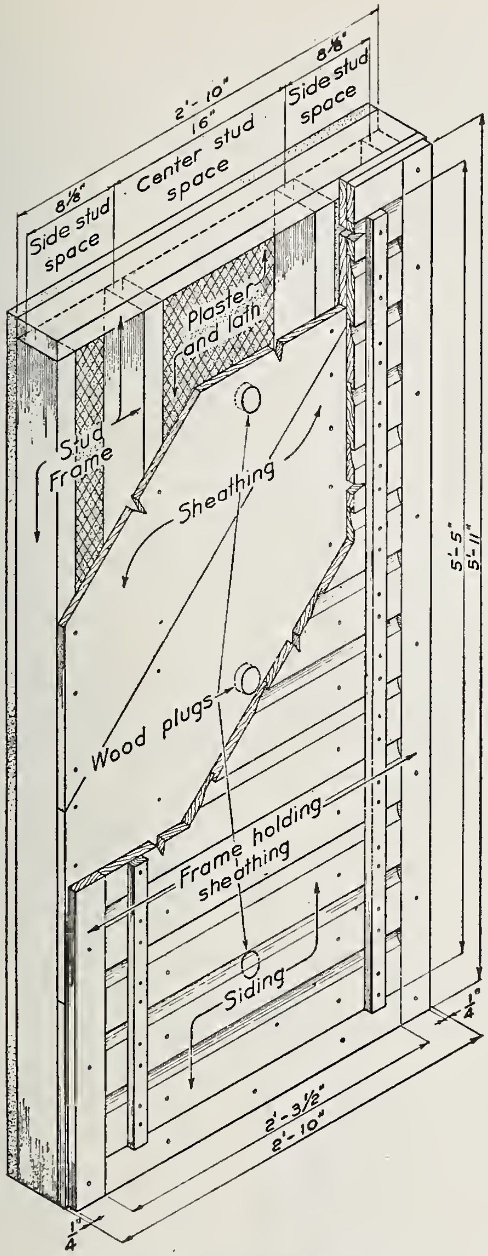

Figure 2.—*Test panel construction.*

sheathing that could be removed and weighed when desired.

IV. TEST METHODS AND CONDITIONS

1. Methods

Prior to each test, the perimeter of the panel was coated with paraffin to prevent gain or loss of moisture through the edges.

Copper-constantan thermocouples in conjunction with a suitable potentiometer were used for all temperature measurements.

There were five thermocouples on each inside and outside surface of the sheathing, siding, and plaster. On each of these surfaces, one of the five thermocouples was located in the middle of the panel. Two of the others were on the horizontal and two were on the vertical center line; each was 5 in. from the edge of the panel.

Five thermocouples were similarly placed in the cold box in a plane about 2 in. from the panel for measuring the air temperature. Four thermocouples were used to measure the air temperature of the hot box.

Electric hygrometers were used for observing the humidity in the stud space. These devices are described in Research Paper RP1102 [2], and a sketch of one is shown in the present paper as figure 3. The device is a glass tube

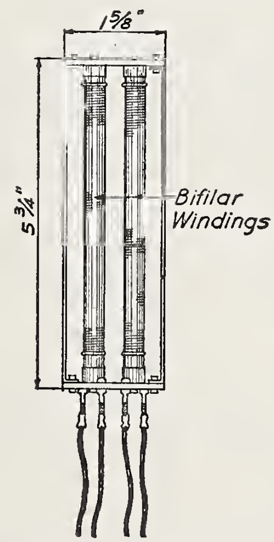

Figure 3.—*Electric hygrometer.*

wound with two coils of wire, the turns of which alternate. The turns do not touch, but are connected electrically only by a hygroscopic film applied after winding. The resistance of this film changes with the humidity of the air to which the device is exposed and is used to indicate the humidity. During use, the temperature of each hygrometer was measured by means of a thermocouple attached to it. In order to calibrate this kind of hygrometer, saturated salt solutions which establish

known relative humidities in enclosures above them were used. Since the hygrometers were not considered stable, they were calibrated before and after each run. The results of some typical calibration tests are shown in figure 4.

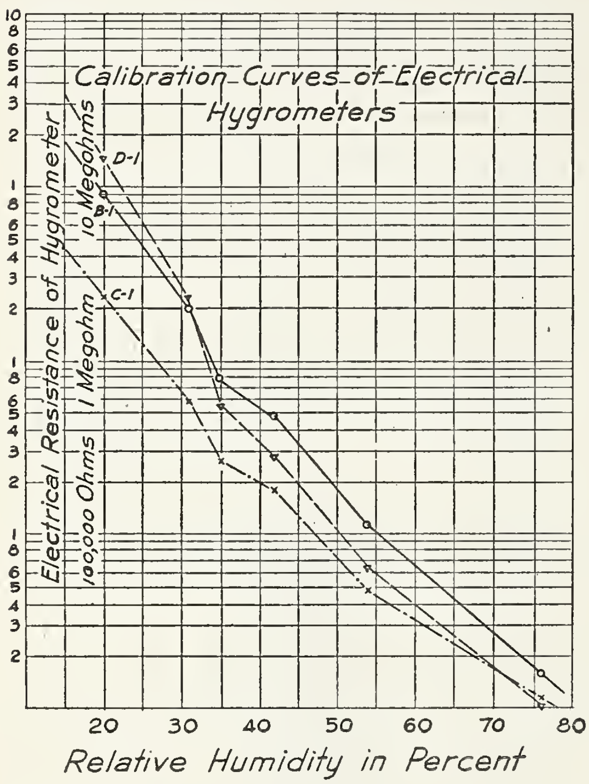

Figure 4.—*Calibration curves of electric hygrometers.*

Improved and more stable instruments have since been perfected and are described in National Bureau of Standards Research Paper RP1265 [3].

The instrument shown in figure 3 consists of two hygrometers in the same frame. An alternating-current ohmmeter was used to measure the resistance of the hygroscopic film.

During the tests with the fill insulation, three of the electric dual-coil hygrometers described above were placed in the stud space of the specimen wall. They were located approximately on the vertical center line of the specimen at points 1 foot from the top, 1 foot from the bottom, and halfway between. The hygrometers were enclosed in wire cages, which prevented contact between their elements and the insulation.

During the tests with blanket insulation, the three instruments were arranged vertically as described above, but they were in the air space on the cold side of the insulation.

During the tests with reflective insulation, only two instruments were used. One was located on each side of the insulating sheet approximately in the middle of the air space.

2. Conditions

It was desired to expose the test panel to severe conditions during these tests. The conditions were 70° F and 30-percent relative humidity on the warm side and −5° F on the cold side. No attempt was made to control the humidity on the cold side. Presumably it was governed by the temperature of the copper wall located near the test panel on the cold side, which would control the dew point in the surrounding air.

Figure 5, a chart similar to one based on a survey described in BMS56, shows that less than 15 percent of the humidified houses sur-

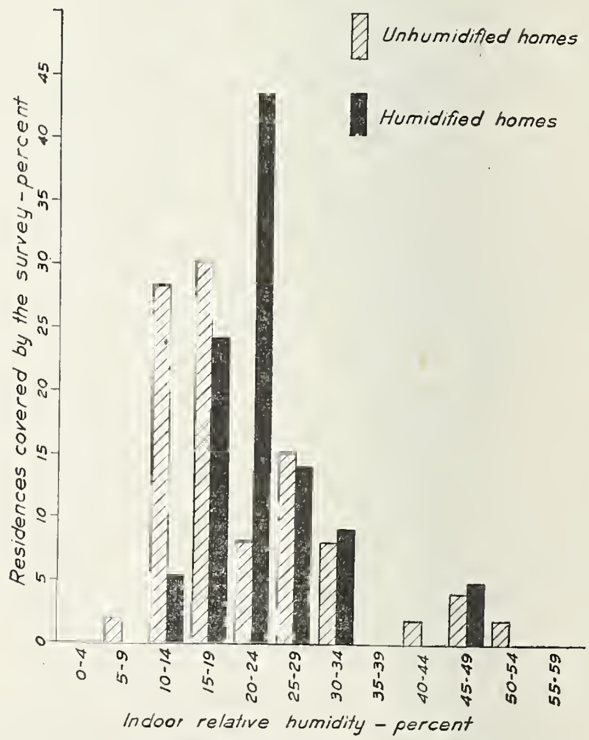

Figure 5.—*Humidity in residences indicated by survey.*

Data obtained between 9 a.m. and 5 p.m. when outside temperature was below 20° F.

veyed had interior relative humidities above 30 percent when the outdoor temperature was less than 20° F. This is construed to mean that, whereas the test conditions probably occur occasionally in houses in the United States, they are more severe than average, even for the cold regions of the country.

V. PROCEDURE AND OBSERVATIONS

During tests A and B, the stud spaces of the panel were filled with 3⅝-in. shredded redwood bark insulating material. During tests A, no vapor barrier was used, while during tests B a barrier of 60-lb asphalt-saturated kraft paper was placed directly behind the plaster. There was no ventilation in either case. The panel arrangement, including the position of the vapor barrier used during tests B, and the vapor pressure and temperature gradients for tests A and B are shown in figure 6.

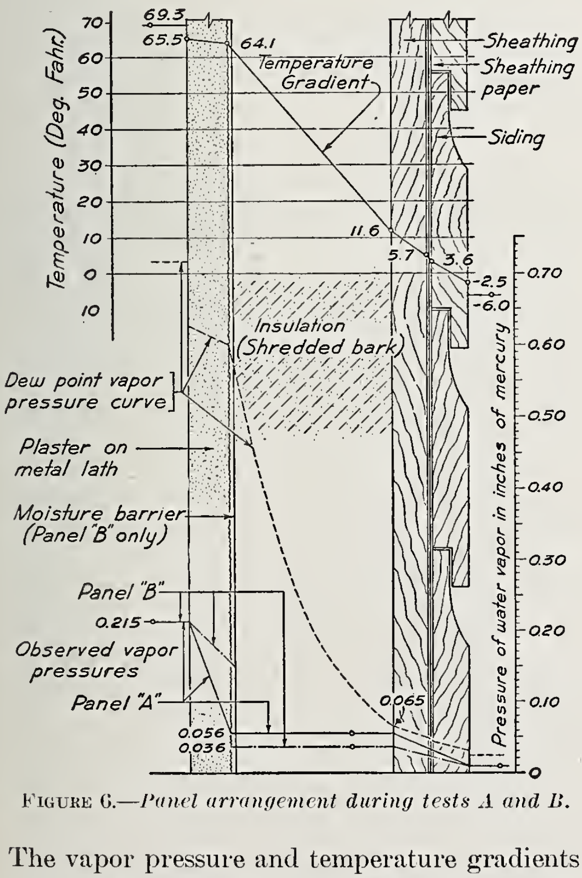

FIGURE 6.—*Panel arrangement during tests A and B.*

The vapor pressure and temperature gradients prevailing throughout both tests are also plotted in figure 6.

The vapor barrier for tests B consisted of a single sheet of asphalt-saturated paper, without joints, located in each stud space. The barrier was sealed by turning the edges flat against the studs or frame at all points and joining them to the wood with Scotch tape around the edges. It was thought that this kind of joint would be superior to any that could be conveniently made by means of nails and wood, but experience during this work showed the need for developing a more satisfactory method of jointing.

From the data summary sheet, table 2, it will be noted that condensation occurred on the sheathing in both tests A and B, and that more occurred in the sheathing during tests B than during tests A, even though a moisture barrier was used only during tests B. This condensation appeared as frost. It was scraped from the sheathing and weighed, and a small amount that melted while the apparatus was being opened was mopped up with absorbent cotton and weighed. The sum of the weights of this water and of the frost is reported on the data sheet as "water condensed on sheathing."

The frost gathered from the sheathing after tests B was obtained from areas near the corners of the panels. It is presumable that the vapor seal was weakest at its corners, and the indication is that leaks existed there, resulting in a heavy deposition of water on the sheathing nearby. It is likely also that the wood of the sheathing, near the corners, became saturated early during the test, so that vapor which condensed later was deposited as frost on the surface of the wood. This probably explains why more frost was gathered after tests B than after tests A, as during tests A the sheathing never became saturated. Such frost as did form during tests A was distributed evenly over the surface of the sheathing.

The effects of the vapor barrier, as shown by tests B, were lower vapor pressure in the stud space, less water evaporated in the hot box, and less water absorbed by the wood, as indicated by the weights of the plugs. These and other data are shown numerically in the data summary sheet, table 2.

TABLE 2.—*Data summary sheet—migration of water vapor through wall*

Data in columns numbered 1 and 2 represent two tests under similar conditions.

Test conditions and results	Tests A		Tests B		Tests C		Tests D		Tests E		Tests F		Tests G		Tests H	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Conditions:																
Hot-box temperature...deg. F..	69.4	69.3	69.2	69.4	------	69.0	68.9	69.0	69.3	69.4	69.2	69.4	69.2	69.3	69.2	69.1
Hot-box relative humidity..%..	29.4	29.9	30.3	29.7	------	29.3	29.4	29.3	29.0	29.9	28.0	28.3	29.4	30.0	30.8	34.2
Hot-box water vapor pressure in Hg..	0.212	0.215	0.217	0.214	------	0.208	0.208	0.208	0.208	0.216	0.201	0.204	0.211	0.215	0.221	0.244
Permeability of vapor barrier (if used).......(g/m²)/24 hr[a]...	------	------	3.82	3.82	------	------	------	------	8.87	8.87	------	------	1.16	1.16	.78	.78
Temperature of sheathing deg F..	11.5	11.3	11.5	12.0	------	18.3	7.3	6.5	8.5	8.7	10.8	10.2	7.5	7.4	6.5	10.6
Dew-point vapor pressure in Hg..	0.065	0.064	0.065	0.067	------	0.094	0.052	0.051	0.055	0.055	0.062	0.060	0.052	0.052	0.051	0.061
Vapor pressure in stud space in Hg..	.064	.048	.028	.043	------	.146 .062	[b].030 [b].037 Below [b]0.012	[b].039 [b].046 Below [b]0.012	Below 0.018	Below 0.019	.062	.061	Below 0.020	Below 0.018	Below 0.016	0.016
Cold-air temperature... deg F..	−6.8	−7.1	−5.1	−5.1	------	−7.1	−6.8	−5.9	−6.5	−6.7	−6.7	−7.3	−7.6	−7.5	−7.3	−5.5
Estimated water vapor pressure in cold air ....in Hg..	0.008	0.006	0.008	0.008	------	0.005	0.005	0.007	0.006	0.007	0.007	0.007	0.005	0.005	------	0.005
Length of test...........hr..	99.7	99.0	99.7	99.5	118.1	99.7	97.0	99.9	97.7	99.0	97.7	99.2	99.1	99.2	98.8	98.5
Results:																
Water evaporated in hot box Grains..	2,020	1,840	170	754	2,200	1,900	1,740	2,160	1,190	1,150	2,110	1,700	1,140	1,090	1,190	538
Water condensed on sheathing Grains.	29	29	93	159	None	None	Trace	None	Noue	None	34	155	131	225	31	12
Water condensed on sheathing paper....... Grains..	None	None	None	None	..do.	..do.	None	..do..	..do..	..do..	None	Nonc	Nonc	Noue	Noue	None
Water condensed on siding Grains.	1.5	Trace	Traee	4.6	..do.	..do.	..do..	..do..	..do..	..do..	..do.	..do.	..do..	..do..	..do..	Do.
Water eoudensed ou copper wall Grains..	216	262	217	312	177	244	1,790	1,630	55	117	80	283	131	182	174	270
Gain of moisture by insulation % by wt..	1.0	0.4	0.1	0.0	------	------	0.1	0.1	------	------	0.0	0.1	------	------	0.0	0.0
Gain of moisture by wood % by wt..	0.76	.76	.43	.48	0.48	0.57	.46	.46	0.0	0.03	.98	.97	0.28	0.20	.08	.31

[a] Values determined by the Paper Section of the National Bureau of Standards by the official method of The Technical Association of the Pulp and Paper Industry.
[b] Upper value is for top of panel, center is for the middle, and lower is for the bottom of panel.

During tests C, aluminum-foil insulation was used. The material was paper, faced on both sides with aluminum foil. It was secured in the stud space midway between the sheathing and the plaster. The joint, consisting of the turned edge secured to the wood by Scotch tape, was used in this case also. There was no vapor barrier in the panel other than the insulating sheet itself and no ventilation.

The panel arrangement and the observed vapor pressure and temperature gradients for tests C are shown in figure 7. The vapor pressure indicated that condensation should not occur, and none was observed when the wall was dismantled. However, some moisture did pass through the wall and condense on the copper sheet on the cold side, as shown in table 2. It is probable that the seal between the insulating sheet and the wood framing was imperfect.

The effect of ventilating the insulated space was studied in tests D. The stud space was filled with rock wool and no vapor barrier was used. The arrangement of the test panel and the vapor pressure and temperature gradients are shown in figure 8. Holes were bored through the outside face of the panel to provide ventilation. A 1-in. hole was bored through sheathing and siding opposite each of the two outer stud spaces at top and bottom, about a foot from the top and the same distance from the bottom. To ventilate the center stud space, the upper and lower moisture-gain measuring plugs were removed during this test.

A trace of moisture was found on the sheathing after the first of the two tests under this condition was made; after the second test, no moisure was found in the panel. The vapor-pressure curves plotted in figure 8 indicate that the conditions necessary for condensation were avoided by a small margin. Furthermore, the water-vapor pressure in the stud space was very low near the ventilating openings and higher near the middle of the panel.

Comparisons of the temperature differences through the plaster during tests D with those that occurred during tests F indicate that the ventilation was responsible for additional heat loss through the panel of approximately 10

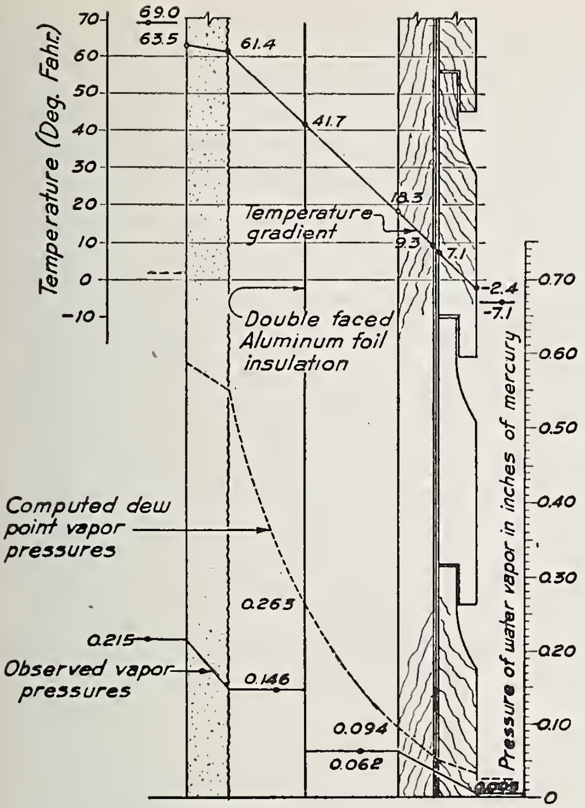

FIGURE 7.—*Panel arrangement during tests C.*

percent. The temperature differences for tests D, F-1, and F-2 were 1.5, 1.4, and 1.3 degrees F, respectively.

During tests E, the stud places were insulated with shredded-wood-fiber blankets composed of wood fibers enclosed in asphalt-impregnated crepe-paper envelopes. Each blanket was 15 in. wide and approximately 1 in. thick and was cut from a roll to a length equal to the height of the panel. They were placed in double thickness in the stud space of the panel with air spaces on the plaster and on the sheathing-side approximately equal. There was no vapor barrier other than the envelope of the blankets and no ventilation.

The arrangement of the wall and the vapor pressure and temperature gradients for tests E are shown in figure 9. No condensation was observed after either of the two tests. The relatively small quantity of water evaporated in the hot box, gained by the plugs in the sheathing and condensed on the copper diaphragm on the cold side, indicates that the blankets were effective in retarding the passage of water vapor through the wall. The fact is not established, however, that the wood fiber did not absorb some moisture during the test. It probably would be necessary to conduct a test of considerably more than 100 hours' duration to determine what happened in this respect. It will be noted from the data summary sheet, table 2, that the vapor permeability of the paper forming the vapor barrier was comparatively high.

For tests, F, G, and H, the stud spaces were filled with rock-wool insulating material. No vapor barrier was used during tests F. During tests G, 2-ply untreated kraft paper with a layer of asphalt between the plies was used as a moisture barrier. In tests H, 2-ply asphalt-saturated kraft paper with a layer of asphalt between the plies was used as a moisture barrier. There was no ventilation.

The arrangement of the panel and the observed vapor pressure and temperature gradients for tests F, G, and H are shown on

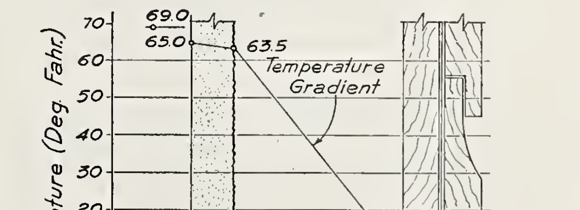

FIGURE 8.—*Panel arrangement during tests D.*

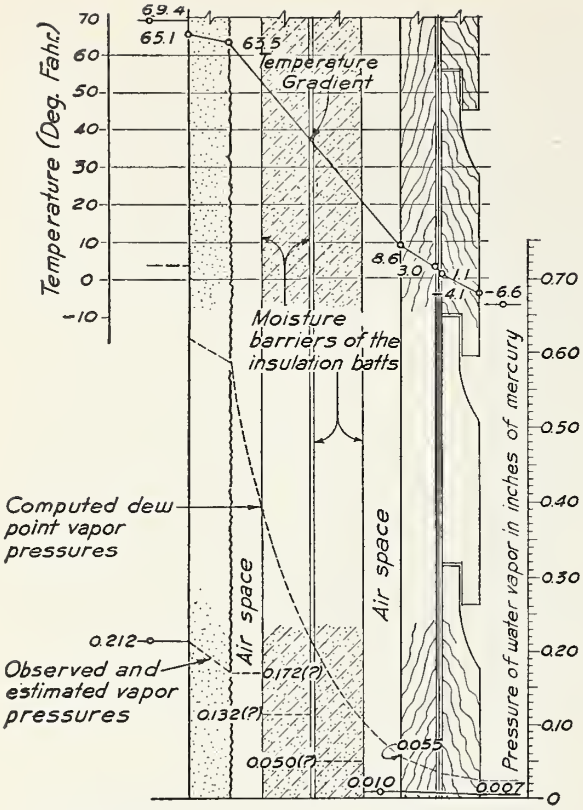

FIGURE 9.—*Panel arrangement during tests E.*

figure 10. The curves indicate that condensation should occur only under the conditions of tests F, when no barrier was used. Nevertheless, condensation also occurred during tests G and H; but this can again be attributed to defects in the seal around the edges of the vapor barrier where it joined the wood, because the frost formed only in the corner. The frost that collected after tests F was evenly distributed over the inner surface of the sheathing.

The data indicate that frost should form under the condition of tests F. The observed vapor pressure in the stud space averaged 0.062 and 0.061 in. of mercury during the two tests, and the dew-point vapor pressure corresponding to the observed temperatures are also 0.062 and 0.061 in. of mercury. The figures check more closely than would be expected from the estimated precision of the apparatus and test method.

The chief effects of the vapor barriers used in tests G and H were the decrease in amount of water necessarily evaporated in the hot box and the lower vapor pressure in the stud space. The difference in the permeabilities of the treated and untreated sisal kraft papers used in tests G and H was not sufficient to make a clearly discernible difference in the observed vapor pressures in the stud spaces.

VI. CONCLUSIONS

The results of the experiments performed with this apparatus indicate that its use is a practicable means of testing wall constructions for condensation under selected conditions of temperature and humidity on the warm and cold sides of the walls. The means for sealing the joint between a paper or metal-foil vapor barrier and framing should be better than the Scotch drafting tape used in this experiment. The failure of this joint during the tests suggests the possibility that vapor barriers in actual use permit the passage of a considerable amount of vapor around their edges.

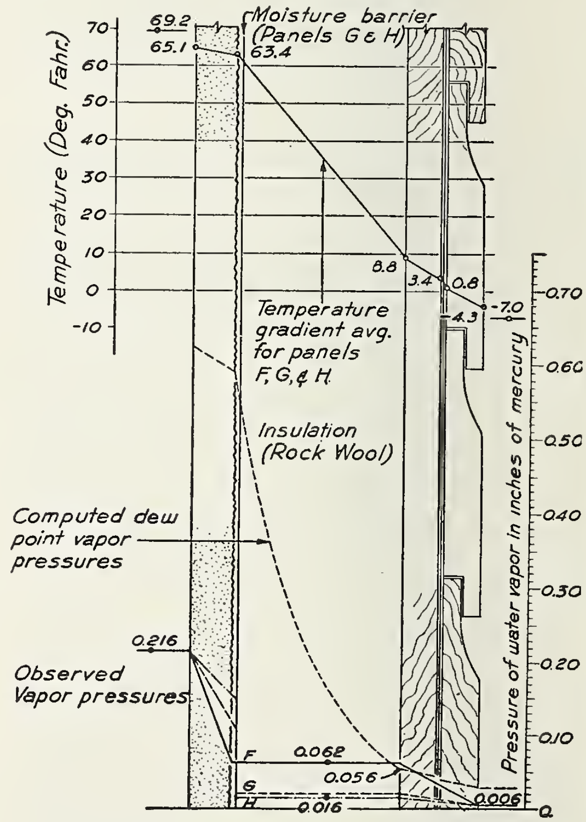

FIGURE 10.—*Panel arrangement during tests F, G, and H.*

The results of tests A indicate that condensation can be expected in a frame wall insulated with $3\frac{5}{8}$ in. of fibrous material if the air on the warm side is maintained at 70° F and 30-percent relative humidity and the air on the other side is maintained at approximately 0° F. The results of tests B show that conditions conducive to condensation in a wall insulated as in tests A can be avoided by means of a vapor barrier with a permeability of 3.8 grams or less per square meter per 24 hours when exposed at 23° C to dry air on one side and 50-percent relative humidity on the other. Most commercial sheathing papers of better grade have a permeability lower than the above value, and therefore can be used effectively as vapor barriers. Asphalt-impregnated paper used as envelopes for insulating blankets was effective in preventing condensation, as shown in tests E. During these tests, 1-inch blankets were installed in double thickness in the middle of the stud space. The blankets consisted of shredded wood fiber enclosed in asphalted paper. A single sheet of metal-foil insulation in the middle of the stud spaces will prevent condensation in the wall under conditions of the above severity, provided the seal at the edges, where the foil is fastened to the studs and frame, is vaporproof. The tests indicated the importance of a good edge seal for paper vapor barriers both for test specimens and in actual use.

WASHINGTON, August 14, 1945.

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